LECTURE # 3

- $\chi f \leftrightarrow \chi f$ IN EARLY UNIVERSE

- INTRO TO IND. DET.

[IF TIME PERMITS...]

THE DM THERMAL HISTORY IS POTENTIALLY IMPORTANT FOR DM STRUCTURE FORMATION, ESP FOR (COLD) "WIMPS"

IN EARLY UNIVERSE, $\chi f \leftrightarrow \chi f$ ($f \in$ THERMAL BATH)

KEEPS DM IN KINETIC EQ EVEN AFTER CHEMICAL FREEZE-OUT (i.e. WHEN $\Gamma_{\chi\chi \leftrightarrow X} \ll H$)

REASON IS THAT TARGET DENSITIES ARE VERY DIFF:

$$\chi\chi \leftrightarrow ff \quad \rightarrow \quad \Gamma = n_{NR}\,\sigma \quad \text{EXP. SUPPRESSED}$$

$$\chi f \leftrightarrow \chi f \quad \rightarrow \quad \Gamma = n_{REL}\,\sigma$$

TYPICALLY, FOR WIMP DM $\sigma_{\chi f \to \chi f} \sim G_F^2 T^2$

HERE, TO ESTIMATE KINETIC DECOUPLING, WE NEED TO ACCOUNT FOR "INEFFICIENT" MOMENTUM TRANSFER:

$\underbrace{\delta p}_{\text{TYPICAL MOMENTUM TRANSFER}} \sim T$ BUT FOR COLD RELICS $\dfrac{p^2}{2m} \sim T$ IN KINETIC EQUILIBRIUM

SO $p \sim \sqrt{mT} \gg \delta p$

MOM. TRANSFER IS STOCHASTIC, SO IT TAKES $\dfrac{1}{N} \approx \left(\dfrac{\delta p}{p}\right)^2 \sim \dfrac{T^2}{mT} = T/m$

SCATTERING TO "ESTABLISH" KINETIC EQUILIBRIUM

SO, HERE, WE WANT TO COMPARE

$$\underbrace{T^3}_{n_{REL}} \cdot \underbrace{G_F^2 T^2}_{\sigma_{\chi f \to \chi f}} \cdot \underbrace{\frac{T}{m_\chi}}_{\left(\frac{\delta p}{p}\right)^2} \sim \frac{T^2}{M_P}$$

SO $T_{kd} \sim \left(\frac{m_\chi}{M_P G_F^2}\right)^{1/4} \sim \left(\frac{100\,\mathrm{GeV}}{10^{18}\,\mathrm{GeV}\,10^{-10}\,\mathrm{GeV}^{-4}}\right)^{1/4} \sim 10^{-\frac{6}{4}} \cdot \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^{1/4} \mathrm{GeV}$

OR $T_{kd} \sim 30\,\mathrm{MeV} \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^{1/4}$

WHAT DOES THIS IMPLY FOR STRUCTURE FORMATION?

ROUGHLY, CUTOFF WILL BE SIZE OF HORIZON AT KINETIC DECOUPLING, SO

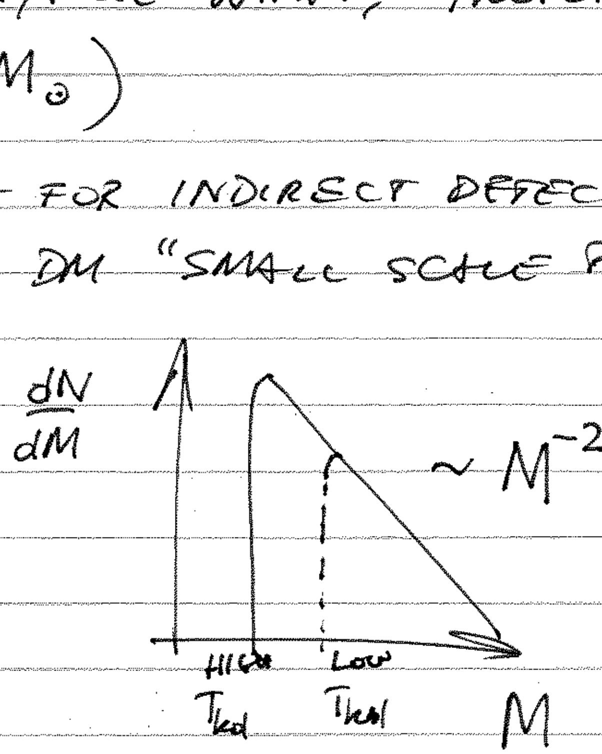
$$M_{kd} \sim \frac{4\pi}{3}\left(\frac{1}{H(T_{kd})}\right)^3 \rho_{DM}(T_{kd})$$

$$\sim 30\,M_\oplus \left(\frac{10\,\mathrm{MeV}}{T_{kd}}\right)^3$$

(MORE PRECISELY: CUTOFF SCALE SET BY LARGEST OF FREE STREAMING ($T_{kd} \gtrsim 0.1\,\mathrm{GeV}$) VS ACOUSTIC DAMPING ($T_{kd} \lesssim 0.1\,\mathrm{GeV}$))

SO, FOR TYPICAL WIMPS, PROTOHALOS HAVE MASS $\sim M_{\oplus}$ (ie $\sim 10^{-6} M_{\odot}$)

IMPORTANT FOR INDIRECT DETECTION (BOOST FACTOR) AND FOR DM "SMALL SCALE PROBLEMS"

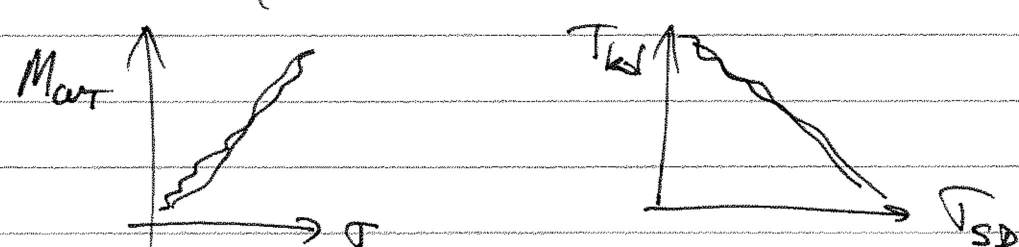


WAYS TO PROBE? $\chi q \to \chi q$ SAME PROCESS AS DIRECT DETECTION!

M_{CUT} CAN CORRELATE WITH $\sigma_{\chi q \to \chi q}$

CAVEAT: USUALLY $T_{kd} < T_{QCD}$ (~ 200 MeV), SO QUARK SCATTERING SECONDARY...

BUT IF (MODEL-DEP.) "QUARK-LEPTON UNIVERSALITY" HOLDS, THEN CORRELATION IS EXPECTED.
AND FOUND (CORNELL + PROFUMO, 2012) e.g.: SUSY, UED



INDIRECT DETECTION

KEY PROCESS: $\chi\chi \to SM$ IN LATE UNIVERSE
(ALSO $\chi \to SM$ DECAY)

KEY INGREDIENTS: (i) PRODUCTION RATES

(ii) ENERGY SCALE

(iii) ANNIHILATION PRODUCTS

RATE FOR GIVEN PARTICLE, IN UNIT VOLUME
e.g.: $e^{\pm}, \bar{p}, \bar{D}, \gamma$'s, ν's

$$= \underbrace{\begin{pmatrix}\#\text{ DM}\\ \text{PAIRS}\\ \text{IN } V\end{pmatrix}}_{\int \frac{\rho_{DM}^2}{m_\chi^2} dV} \times \underbrace{\begin{pmatrix}\text{PAIR}\\ \text{ANNIHILATION}\\ \text{RATE}\end{pmatrix}}_{\langle\sigma v\rangle(T=0)} \times \underbrace{\begin{pmatrix}\#\text{ OF}\\ \text{PARTICLES}\\ \text{PER ANN.}\\ \text{EVENT}\end{pmatrix}}_{m_\chi,\ \text{ANN FINAL STATE}}$$

TALKED ABOUT $\langle\sigma v\rangle$, m_χ ; ANN FINAL STATE ?

ANNIHILATION FINAL STATE

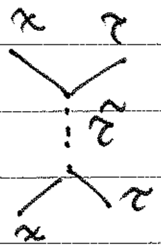
IF DM IS MAJORANA $\longrightarrow$ $\chi\chi \xrightarrow{\text{PSEUDOSCALAR}} f\bar{f}$ REQUIRES HELICITY FLIP $\longrightarrow$ $|M|^2 \propto m_f^2$ (EXACTLY AS FOR $\pi^\pm$ DECAY!)

SO: NO LIGHT FERMIONS! $\overleftarrow{f}\ \overrightarrow{\bar{f}}$

IF $m_\chi \lesssim m_{top}$ AND χ DOESN'T LIKE W^+W^-, ZZ, hh

$$\Longrightarrow \chi\chi \to \underbrace{\bar{b}b}_{3\times\text{ COLOR}},\ \tau^+\tau^- \text{ DOMINANT}$$

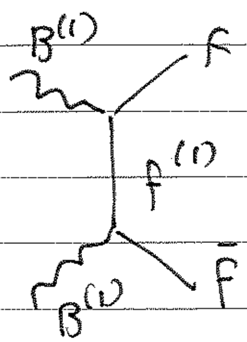
$\tau^+\tau^-$ CAN BE BOOSTED, e.g., WITH LIGHT $\tilde{\tau}$ IN SUSY:



(TRUE IN mSUGRA/CMSSM)

... BUT KILLED BY $m_h \sim 125$ GeV

TOTALLY OPPOSITE FOR UED, $B^{(1)} \propto$ HYPERCHARGE



$$|M|^2 \sim |Y_f|^4$$

LIKES $u_L : |Y_f| = \frac{4}{3}$, $e_R : |Y_f| = 2$

IN SU(2) MULTIPLETS (e.g. HIGGSINOS, WINOS IN SUSY) EVERYTHING IS FIXED BY GAUGE INTERACTIONS

WINOS : FINAL STATES: W^+W^-

(SU(2) TRIPLET) $\tilde{\chi}^\pm$

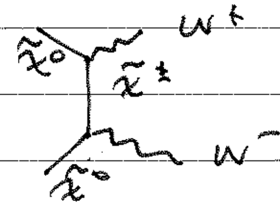
$\tilde{\chi}^0$ $\quad$ δm $\quad \sim M_2$

~ 10's MeV

$$\langle \sigma v \rangle_{\tilde{W}} \simeq \frac{3}{16\pi}\frac{g^4}{M_2^2}$$

EXACTLY STRUCTURE WE POSTULATED!

$\longrightarrow$ INCLUDES



$$\Omega_{\tilde{W}} h^2 \simeq 0.1 \left(\frac{M_2}{2.2\,\text{TeV}}\right)^2$$

HIGGSINOS : FINAL STATES: W^+W^-, ZZ

(SU(2) DOUBLETS) $\tilde{\chi}^\pm$ $\tilde{\chi}^0_2$

$\tilde{\chi}^0_1$ $\quad \sim \mu$

$$\langle \sigma v \rangle_{\tilde{H}} \simeq \frac{g^4}{512\pi\mu^2}\left(21 + 3\tan^2\theta_W + 11\tan^4\theta_W\right)$$

$$\Omega_{\tilde{H}} h^2 \simeq 0.1 \left(\frac{\mu}{1\,\text{TeV}}\right)^2$$